Fusion Engineering and Design 87 (2012) 13–22

Contents lists available at SciVerse ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Thermo-hydraulic analysis of the generic equatorial port plug design

E. Rodríguez[a,*], J. Guirao[b], J. Ordieres[b], J.L. Cortizo[a], S. Iglesias[b]

[a] Department of Mechanical Engineering, University of Oviedo, Campus de Gijón, 33203 Gijón, Spain
[b] Numerical Analysis Technologies, S.L, Marqués de San Esteban No 52, 33206 Gijón, Spain

ARTICLE INFO

Article history:
Received 9 May 2011
Received in revised form 11 August 2011
Accepted 16 August 2011
Available online 13 September 2011

Keywords:
Thermo-hydraulic
Equatorial port plug
Finite element, ITER

ABSTRACT

The port-based ITER diagnostic systems are housed primarily in two locations, the equatorial and upper port plugs. The port plug structure provides confinement function, maintains ultra-high vacuum quality and the first confinement barrier for radioactive materials at the ports. The port plug structure design, from the ITER International Organisation (IO), is cooled and heated by pressurized water which flows through a series of gun-drilled water channels and water pipes. The cooling function is required to remove nuclear heating due to radiation during operation of ITER, while the heating function is intended to heat up uniformly the machine during baking condition. The work presented provides coupled thermo-hydraulic analysis and optimization of a Generic Equatorial Port Plug (GEPP) structure cooling and heating system. The optimization performed includes positioning, minimization of number and size of gun drilled channels, complying with the flow and functional requirements during operating and baking conditions.

1. Introduction

One of the milestones of the design activity of a representative GEPP was to carry out thermo-hydraulic analysis of the GEPP structure's cooling system and to perform design modifications in the light of the analysis results.

A previous thermal and hydraulic analysis of the cooling systems of the ITER equatorial port plugs was used [1]. This analysis was focused on calculating the main hydraulic parameters for the reference cooling circuit and the cooling requirements for the Diagnostic Shield Modules (DSM). The thermal assessment of the port plug under neutronic load during normal operation, with the optimization of the cooling system, was studied in [2]. In [3] structural, thermal, neutronic and electromagnetic analyses of port plug were performed.

The scope of the present analysis was to optimize the GEPP box structure's cooling system through the adequate positioning and the minimization of number and size of gun drilled channels. This was carried out considering ITER specific requirements [4], and also taking into account manufacturing features in the redesign. This paper summarizes the results of the thermo-hydraulic analysis and subsequent GEPP structure's cooling circuit redesign.

2. Finite element model description

To perform the thermo-hydraulic analysis optimization, two 3D finite element models were created (Fig. 1).

The first model was built with Ansys 11.0 Multiphysics [5] software to perform coupled thermal-hydraulic analysis of the EPP structure and cooling/heating channel system. It accurately represents the EPP and the VV port flange geometry and the main parameters and dimensions of their cooling channel systems. This allows iterative analysis for optimization of the channel system geometry, number and size of channels and general thermo-hydraulic performance.

Channel mass flow and convective heat exchange between fluid and structure were implemented in this model, but it did not include local pressure drop in the circuit singularities such as elbow connectors, corners or T connectors.

The second model, built with Ansys 12.0 CFD software, accurately represents the cooling channel system geometry and flow parameters obtained from the first model. It allowed a more detailed fluid dynamic analysis to verify and define in detail the hydraulic performance of the cooling/heating circuit. Pressure drop of all elements in the cooling system was therefore taken into account in the analysis performed on this model.

2.1. Element types

For thermal analysis, structured mesh parts were built using SOLID70 elements. Non structured parts were built using SOLID90 elements. For the simulation of realistic contact interactions

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* Corresponding author. Tel.: +34 985181944; fax: +34 985181945.
E-mail address: eduardo@uniovi.es (E. Rodríguez).

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doi:10.1016/j.fusengdes.2011.08.007

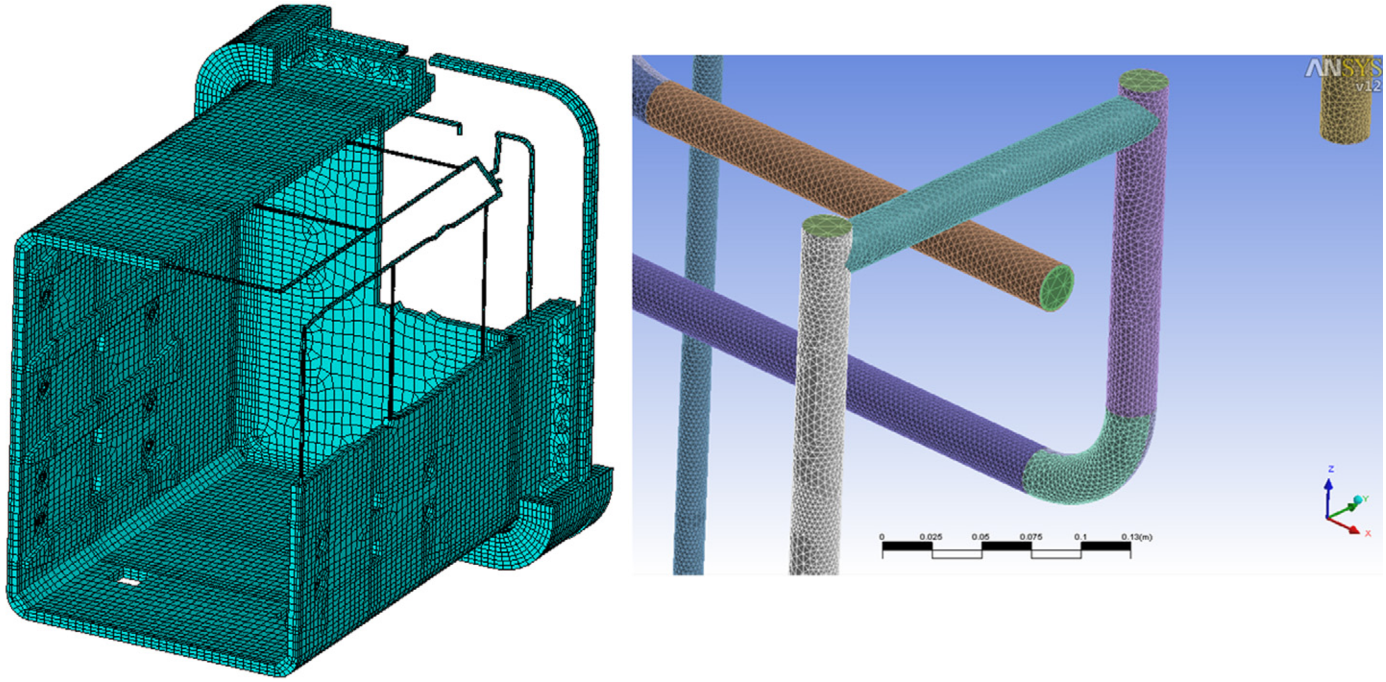

Fig. 1. Finite element models including: (1) EPP structure, guide rails for DSM drawers and VV port flange and (2) EPP structure cooling channels system for CFD analysis.

between EPP flange and VV port flange, thermal contacts have been included in the model using CONTA174 and TARGE170 elements.

For hydraulic analysis, cooling channels were modeled using FLUID116 element. This is a 3D element with the ability to conduct heat and transmit fluid between its two primary nodes. Heat flow was due to the conduction within the fluid and to the mass transport of the fluid. Convection may be accounted for with additional nodes and convection areas. The film coefficient was related to the fluid flow rate.

To perform a coupled thermo-hydraulic analysis between the cooling system and the EPP structure, LINK34 elements were used. LINK34 is a uniaxial element with the ability to convect heat between its nodes. The thermo-hydraulic finite element model has 128,590 nodes and 432,300 degrees of freedom (DOF). The CFD finite element model has 1,515,088 nodes.

2.2. Material models

For thermal analysis, temperature dependent material properties have been considered. These properties were obtained from [6,7] for the SS 316LN IG (Table 1). Table 2 shows cooling temperature dependent properties.

3. Loading conditions

According to the Generic Diagnostic Port Plug requirements document [4]:

- The port plug structure and its contents are heated by plasma radiation (neutrons, gammas and electromagnetic radiation). The generic port plug design is expected to demonstrate that it will meet all applicable requirements under such radiation heat loads. Acceptable levels for nuclear heating are dependent on the thermal design of the port plug structure.
- The port plug is baked with blanket water at a temperature of 240 °C. The minimum required baking temperature of the port plug structure and internal components is 200 °C. The maximum time allowed to reach this baking temperature, at all points within the port plug structure from room temperature is 100 h. Ramp-up time of the water temperature, from room temperature to baking temperature, is 48 h. The minimum baking time is determined by allowable thermal stresses.

Therefore for the present analysis two different thermal loading cases were considered.

3.1. Loads for operating conditions

The first thermal load case represents the nuclear heating during the operation. Fig. 2 shows the nuclear heating volumetric loads as a result of the preliminary neutronic analysis of the port plug structure [8].

The distribution of the heating with the radial coordinate was used. In order to apply this volumetric heating load to the FE model elements, a routine was created that selects every element in the model, calculates its centroid radial position and finally assigns the correspondent volumetric heat generation rate (W/m^3). Fig. 3 shows the volumetric distribution of the heat generation rate considered for the analysis, obtained from the neutron radiation heating profile.

As can be observed from Figs. 2–3, there is a strong dependence between the generation rate and radial coordinate so slight differences in length of the designs mean important variations in the amount of nuclear heating applied in the analysis.

Total generation rates will then depend on the quantity of material and on its distribution with respect to the radial coordinate. The maximum nuclear heating power generation at the front of the port plug structure was 6880 W and the maximum local heat generation rate was 150,352 W/m^3.

During operation the heat loads on the plug are due to volumetric nuclear heating, and cooling is provided by the water circuit. Since the cooling water inlet temperature was 100 °C, convection heat exchange conditions in internal coolant channels were also considered. In this case the analysis was static and the permanent temperature distribution during operation was obtained.